Economic sustainability of biogas production from animal manure: A regional circular economy model

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Abstract

In the context of the circular economy, cooperation among agriculture, animal farming and bioenergy production based on local second generation biomass use and by-product exchange may yield innovative regional business models. Actors from such different sectors can enhance the development of a circular economy on a local level, gaining economic advantages for themselves and contributing to generate environmental benefits. However, as second generation biomass is not produced upon demand but emerges as secondary output, spatial, technical, and technological variables cause uncertainties on economic benefits for the actors involved. These uncertainties may impede local actors to get engaged with innovative circular economic business models, thus hindering the generation of environmental advantages.

This paper proposes a circular economy model where animal manure is used to produce biogas and alternative fertilizer, where the latter, in turn, is used in agricultural activities in a regional network of suppliers and producers. The empirical case of this study is based on the use of cattle and pig manure in biogas production in a case example. The impacts of the above-mentioned variables on the economic returns for each actor are investigated numerically using an enterprise input-output approach. The analysis identifies under which conditions cooperation can be beneficial for all actors involved. Accordingly, different cooperation modes are proposed from an organizational perspective.

The paper provides theoretical, practical and managerial contributions for the regional actors to design such circular economic business models with reduced environmental impacts. Implications derived from resource and energy savings in the specific case of biogas production are also interpreted from a regional policy-making perspective.

Keywords: biogas production, circular economy, sustainable bioenergy, circular business models

1. Introduction

Since the industrial revolution, the world economy has followed a 'take-make-consume and dispose' pattern of growth, a linear model based on the assumption that resources are abundantly available, easy to source and cheap to dispose of (European Commission, EC, 2015). Such a model causes large

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environmental pressure on the planetary boundaries because it is characterized by a high consumption of raw materials and relatively high waste during production. The resulting waste is in turn may be disposed using landfill.

Such models are not sustainable from an environmental point of view. In particular, the increasing awareness that natural resources are limited pushes towards the development and the implementation of new circular economy models, able to manage existing resources in a continuous cycle, hence providing an effective use of these resources. In this regard, the European Commission claims that circular economy may be able to provide economic benefits for firms in addition to environmental benefits, and widely recommends their adoption (EC, 2015).

Within this framework, an important issue concerns the energy production. Since about 60% of the total electric energy is produced from fossil fuels (International Energy Agency, 2014), the energy generation is one of the main reasons of greenhouse gas emissions (Soytas et al., 2007), which in turn are widely recognized as the main driver of climate change (IPCC, 2014). With the aim to mitigate this problem, alternative technologies have been developed to produce energy from renewable resources. A well-known example of the latter is the production of energy from second-generation biomass (McKendry, 2002; Albino et al., 2015). Second-generation biomass refers to organic wastes and residues: solid and liquid municipal wastes, manure, lumber and pulp mill wastes, and forest and agricultural residues (Hall and House, 1994; Miyamoto, 1997). First generation biomass refers to organic products that principally were used to produce food; its use generated a large ethical debate, and it is therefore that the restriction to the use of second generation biomass is widely promoted.

In particular, the use of manure for energy production may offer remarkable opportunities at places where intensive livestock farming is practiced (Massaro et al. 2015). Technologically speaking, manure-based bioenergy can be produced in two different ways: (i) producing biogas by anaerobic digestion (AD) and (ii) producing biochar, bio-oil and gases through pyrolysis (P) (Beardmore, 2011). In both cases, the resulting products can be used as fuel to generate electric energy. Currently, AD ensures the highest performance from both an environmental and an economic point of view (Miller and Moyle, 2014).

Since in the Netherlands intensive livestock farming is practiced, the amount of manure produced is considerable and its exploitation for bioenergy production may have a remarkable potential. However, the possibility to produce manure-based energy is actually not fully exploited due to obstacles in the cooperation of manure producers and biogas producers (De Korte, 2012). As a consequence, the potential environmental and economic benefits are not achieved.

This paper analyzes the biogas manure-based supply chain, i.e., the biogas production from manure by anaerobic digestion. Through a case example, the paper aims to identify the main variables affecting the cooperation dynamics among manure producers and biogas producers. To this end, we model the biogas manure-based supply chain through an Enterprise Input-Output (EIO) approach, identifying the technical and economic variables affecting the environmental and economic benefits generated. Then, we use numerical analysis via computational experiments to assess the impacts of the above-mentioned variables on the supplier-buyer relationships in the local markets, in order to foster cooperation and to stimulate the production of renewable energy. Besides, our work provides practical and managerial contributions aimed at enhancing the development of circular economy models on a local level.

The remainder of the paper is organized as follow. Section 2 presents the generic EIO model for supply chains and Section 3 addresses EIO model application in the case example. In Section 4, the circular business model is presented and a scenario analysis is proposed to reveal the role of uncertainty on cooperation decisions. The experimental results are presented and discussed in Section 5. We end this paper with conclusions in Section 6.

2. Enterprise input-output model for supply chains

In this section, we use a physical enterprise input-output (EIO) model to quantify the material/energy/waste flows of the biogas supply chain (BGSC) and integrate it into the monetary EIO model in order to calculate the economic performance of the BGSC. The generic EIO model for supply chains is adopted from Yazan et al. (2011).

The functional unit of the supply chain is modelled as a process that transforms inputs into outputs and produces wastes from the transformation. The process may require two kinds of input: (i) primary inputs, which are purchased from outside the supply chain; (ii) main inputs, which come from other processes belonging to the supply chain (outputs produced by other processes). We assume that each process can require more than one input and generate more than one waste. However, for the sake of simplicity, we suppose that each process can produce only one output (which means that the term “output” in the sequel may refer both to the main product as well as to the process producing that product). Figure 1 displays a simple representation of a supply chain process from an input-output perspective.

Let us consider a supply chain composed of n processes. We define $\mathbf{Z_0}$ as the matrix of domestic intermediate deliveries between processes, $\mathbf{f_0}$ as the vector of final demands, and $\mathbf{x_0}$ as the vector of gross outputs. The matrix $\mathbf{Z_0}$ is of size n x n, and both vectors $\mathbf{f_0}$ and $\mathbf{x_0}$ are of size n x 1. The intermediate coefficients matrix $\mathbf{A}$ is defined as follows:

$$\mathbf{A} = \mathbf{Z_0}\hat{\mathbf{x}}_\mathbf{0}^{-1} \tag{1}$$

where $\hat{\mathbf{x}}_\mathbf{0}^{-1}$ denotes the diagonal matrix with elements $\mathbf{x}_{\mathbf{0}i}^{-1}$ on the diagonal and zero elsewhere. An element of the intermediate coefficients matrix, i.e., a_{ij}, denotes the necessary quantity of input i to produce one unit of output j. Therefore, we have (note that the spectral radius of the nonnegative matrix $\mathbf{A}$ is smaller than one):

$$\mathbf{x_0} = \mathbf{A}\mathbf{x_0} + \mathbf{f_0} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f_0} \tag{2}$$

Besides, there are s primary inputs purchased from outside the supply chain and m by-products and wastes are produced as secondary outputs within the supply chain. $\mathbf{r_0}$ is the primary input vector (size s x 1) and $\mathbf{w_0}$ the by-product/waste vector (m x 1).

Let $\mathbf{R}$ denote the s x n matrix of primary input coefficients, with the element r_{kj} denoting the use of primary input k (1,…,s) per unit of output of process j, and let $\mathbf{W}$ denote the m x n matrix of waste and by-product coefficients, with the element w_{lj} denoting the output of by-product or waste type l (1,…, m) per unit of output of process j. $\mathbf{R}$ and $\mathbf{W}$ are observed data matrices. Hence:

$$\mathbf{r_0} = \mathbf{R}\mathbf{x_0} \tag{3}$$

$$\mathbf{w_0} = \mathbf{W}\mathbf{x_0} \tag{4}$$

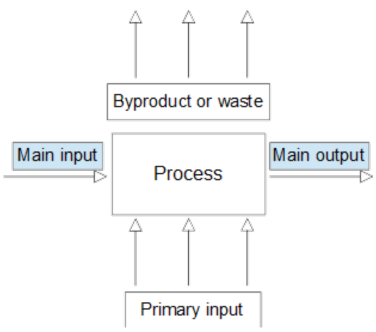

Figure 1. A supply chain process from an input-output perspective

To describe the monetary EIO model, we first introduce the unitary cost and price vectors. $\mathbf{p_0}$ is the vector (*n* x 1) of the prices, with the element p_i indicating the unitary price of the main product of process *i.* Therefore, using the vector of gross outputs $\mathbf{x_0}$, we can calculate the vector $\mathbf{y_0}$ (*n* x 1), representing the total revenues associated with each gross output as follows:

$$\mathbf{y_0} = \hat{\mathbf{x}}_0 \mathbf{p_0} \tag{5}$$

Furthermore, we can determine the monetary coefficients matrix $\mathbf{B}$ (*n* x *n*), with the generic element b_{ij} expressed as:

$$b_{ij} = a_{ij} \frac{p_i}{p_j} \tag{6}$$

Then, we can determine $\mathbf{y_0}$ as follows:

$$\mathbf{y_0} = \mathbf{B}\mathbf{y_0} + \hat{\mathbf{f}}_0 \mathbf{p_0} = (\mathbf{I} - \mathbf{B})^{-1} \hat{\mathbf{f}}_0 \mathbf{p_0} \tag{7}$$

with $\hat{\mathbf{f}}_\mathbf{0}$ denoting the diagonal matrix with elements $\hat{\mathbf{f}}_{0i}$ on the diagonal and zero elsewhere. Moreover, we define the vector of prices (or costs) $\mathbf{p_0^w}$ (*m* x 1)*,* where the generic element p_i^w represents the unitary price (or cost) associated with the by-products (or wastes) in all processes (i.e., by-products represent economic gains and waste represents treatment costs). Hence, using the matrix $\mathbf{W}$, we can identify the vector $\mathbf{y_0^w}$ *,* a *n* x 1 vector*,* representing the total revenues associated with all by-products and wastes for each process as follows:

$$\mathbf{y_0^w} = [(\mathbf{p_0^w})^\mathbf{T} \mathbf{W} \hat{\mathbf{x}}_\mathbf{0}]^\mathbf{T} \tag{8}$$

In addition, let $\mathbf{p_0^r}$ (*s x* 1) be the unitary primary input prices vector. Then, we can compute $\mathbf{y_0^r}$ (*n* x 1), the vector of the costs associated to each process for the primary inputs purchasing (including workforce).

$$\mathbf{y_0^r} = [(\mathbf{p_0^r})^\mathbf{T} \mathbf{R} \hat{\mathbf{x}}_\mathbf{0}]^\mathbf{T} \tag{9}$$

The vector of intermediate inputs costs $\mathbf{y_0^z}$ (*n* x 1), is also calculated using $\mathbf{p_0}$ and $\boldsymbol{i}$ (*n* x 1 unit vector, having all elements equal to one).

$$\mathbf{y_0^z} = [(\mathbf{i})^\mathbf{T} \hat{\mathbf{p}}_\mathbf{0} \mathbf{A} \hat{\mathbf{x}}_\mathbf{0}]^\mathbf{T} \tag{10}$$

Finally, we introduce $\mathbf{d_0}$, which is a *n* x 1 vector representing the amortization costs. The generic element d_i represents the annual amortization cost of process *i*. Then, the profit of the whole production chain (Π) can be computed as:

$$\Pi = \sum_{i=1}^{n} (y_i + y_i^w - y_i^z - y_i^r - d_i) \tag{11}$$

3. The manure-based biogas supply chain: a case example

In this section, we assess the manure-based biogas supply chain adopting the EIO approach. The main production processes within the manure-based biogas supply chain are presented in Figure 2. Manure is collected from farms, loaded into trucks and transported to the biogas plant. Then, manure is mixed with other types of biomass in order to increase biogas yield in later stages. In this paper, we assume the use of corn silage for the mixing process. The obtained blend is converted into biogas and digestate (a nutrient-rich material useable as alternative fertilizer) by means of anaerobic digestion where microorganisms break down the biodegradable material in the absence of oxygen (American Biogas Council, 2014). Afterwards, biogas is used for combined heat and power (CHP) generation for the production of electricity and heat (American Biogas Council, 2014).

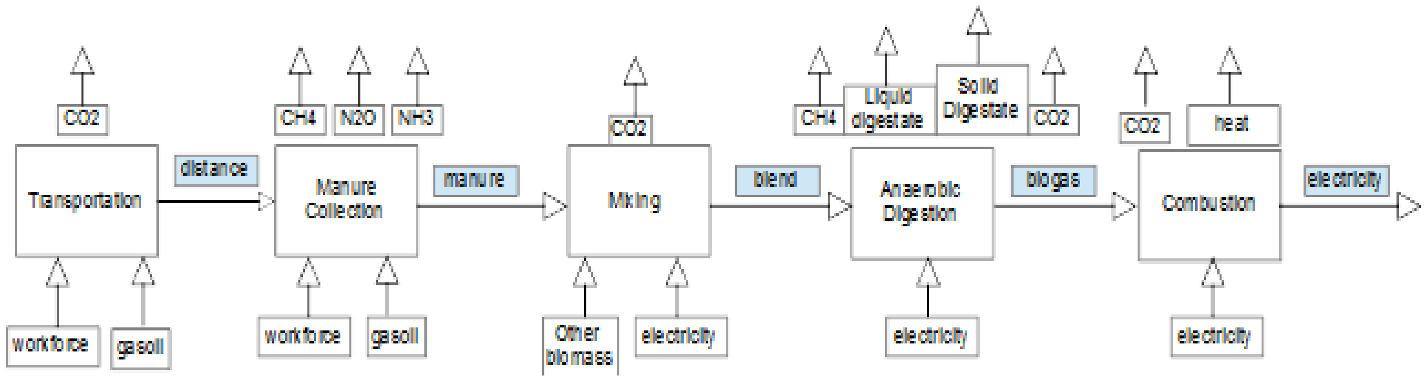

Figure 2. Manure-based biogas supply chain flowchart

Accordingly, five main processes are considered: manure collection (P1), transportation (P2), mixing (P3), anaerobic digestion (P4), and combustion (P5). Each process receives a main input and produces a main output. All these outputs are physical products, except for the output of the transportation process, which is the distance covered between the manure producer and the biogas producer. There are also four primary inputs (gasoil, workforce, electricity, other biomass), four wastes (CO_2, N_2O, CH_4, NH_3), and three by-products sold as a value-added (solid and liquid digestate, heat).

In this section we apply the EIO model to a numerical case example assuming fix costs and prices for a small-scale biogas plant. The computations of this section are the basis of the next section where we describe the circular business model scenario and apply computational experiments to reveal the role of five decision variables on chains' economic performance.

In the base scenario, we assume 5,000 ton of cattle manure and an average transportation distance of 3 km between the farm and the small-scale biogas plant. Values of technical parameters are extracted from literature. In particular, the available literature shows different dry content for cattle manure, which varies between 8-12%, and different organic content, which varies from 80 to 85% (Navaratnasamy et al., 2013). We assume 12% of dry content and 85% of organic content in our base scenario. In the mixing process, we assume a mixture rate of 98% manure and 2% corn silage. From one ton of manure it is possible to produce 0.8 ton of digestate (Berglund et al., 2006). The cogeneration process can produce 1.7 kWh of electricity and 7.7 MJ of heat from the exploitation of 1 m^3 of biogas (Navaratnasamy et al., 2013). Table 1 and 2 present the physical and monetary input-output tables, respectively.

Table 1 shows that in the base scenario the plant produces 192 t of CO_2, 612 t of solid digestate, 3,468 t of liquid digestate, 315,783 KWh of heat and 251,090 KWh of electricity per year.

We apply 10% mark-up for the final products of the bio-energy plant while the manure, gasoil, and corn silage prices are considered fixed on 2 €/t, 1.2 €/liter, and 40 €/ton respectively. Since the literature shows that economic value of digestate ranges from 0.5 to 3.2 €/t (Lantz et al., 2013), we assume an average price of 1.85 €/t digestate. According to Navaratnasamy et al. (2013), the capital costs of a small-sized biogas plant are 6,510 €/KWh and the running costs 0.019 €/KWh. Furthermore, government incentives for renewable energy production are 0.056 €/KWh.

We see from Table 2 that the chain produces a total annual value-added of 84K € with a loss of 58K € and employment of 142K € in the base scenario, where value-added is measured as the sum of profit and wages. We understand from the base scenario that small-scale cattle manure-based biogas plant is not profitable. We show in section 4 that the medium-big scale biogas plants can be profitable under certain conditions.

	Processes		Process 1	Process 2	Process 3	Process 4	Process 5	Final Demand	Total Production
P1	Collection	ton of manure	0	0	5,000	0	0	0	5,000
P2	Transportation	km	2,143	0	0	0	0	0	2,143
P3	Mixing	ton of blend	0	0	0	5,100	0	0	5,100
P4	Anaerobic digestion	m3 of biogas	0	0	0	0	147,700	0	147,700
P5	Combustion	Kwh of electricity	0	0	0	0	0	251,090	251,090
	Primary inputs							**Total primary input use**	
r1	gasoil	liter	700	3,500	0	0	0	4,200	
r2	workforce	person.hour	4,000	667	1,600	1,600	1,600	9,467	
r3	other biomass	ton	0	0	100	0	0	100	
r4	electricity	KWh	0	0	4,781	125,545	125,545	255,871	
	By-products and wastes							**Total by-products and wastes**	
w1	CO2	ton	1.8	9	2	55	124	192	
w2	CH4	ton	19,598	0	0	0.01	0	20	
w3	N2O	ton	0.050	0	0	0	0	0	
w4	NH3	ton	1,400	0	0	0	0	1	
w5	solid digestate	ton	0	0	0	612	0	612	
w6	liquid digestate	ton	0	0	0	3,468	0	3,468	
w7	heat	kWh	0	0	0	0	315,783	315,783	

Table 1. Physical input-output table of the manure-based biogas supply chain

	Processes	Process 1	Process 2	Process 3	Process 4	Process 5	Final Demand	Total Production
P1	Collection	0	0	10,000	0	0	0	10,000
P2	Transportation	2,657	0	0	0	0	0	2,657
P3	Mixing	0	0	0	43,440	0	0	43,440
P4	Anaerobic digestion	0	0	0	0	80,176	0	80,176
P5	Combustion	0	0	0	0	0	131,208	131,208
	Primary inputs						**Total primary input use**	
r1	gasoil	840	4,200	0	0	0	5,040	
r2	wages	60,000	10,000	24,000	24,000	24,000	142,000	
r3	other biomass	0	0	4,000	0	0	4,000	
r4	electricity	0	0	267	7,031	7,031	14,329	
	By-products and wastes						**Total by-products and wastes**	
w1	CO2	27	136	31	822	1,842	2,859	
w2	CH4	2,744	0	0	1	0	2.745	
w3	N2O	0	0	0	0	0	0	
w4	NH3	0	0	0	0	0	0	
w5	solid digestate	0	0	0	1,132	0	1,132	
w6	liquid digestate	0	0	0	6,416	0	6,416	
w7	heat	0	0	0	0	1,042	1,042	

	Amortization cost	1.333	10.000	5.141	5.141	5.141		26.757
	Total Costs	67.602	24.336	43.440	72.887	117.147		325.412
	Profit	-57.602	-21.679	0	7.289	14.061		-57.931
	Value-added	2.398	-11.679	24.000	31.289	38.061		84.069

Table 2. Monetary input-output table of the manure-based biogas supply chain

4. Circular business model scenario

Since bioenergy supplier and buyer networks are characterized by a notable level of uncertainty, our next step is associated with revealing the role of variables influencing the chain performance and decisions-to-cooperate of biogas supply chain actors. We consider two actors in the manure-based biogas supply chain: a farmer (***f***) and a bioenergy producer (***b***). As an addition to the base scenario, we assume that the farmer is also a cultivator, meaning that the digestate produced by the bioenergy producer can be used by the farmer in cultivation of sunflowers. Figure 3 displays the simple input/output flows of such a circular business model.

We evaluate two scenarios: (i) non-cooperation and (ii) cooperation. In the former, the farmer produces manure which is used as fertilizer for sunflowers cultivation and the biogas plant is not part of the business (model). In the cooperation scenario, the farmer produces manure which is sent to the biogas plant. The biogas plant produces biogas (used for electricity and heat production) and digestate which is sold to the farmer. The farmer uses digestate as fertilizer for sunflowers production. Therefore, local farmers are confronted with a decision to be involved in energy production.

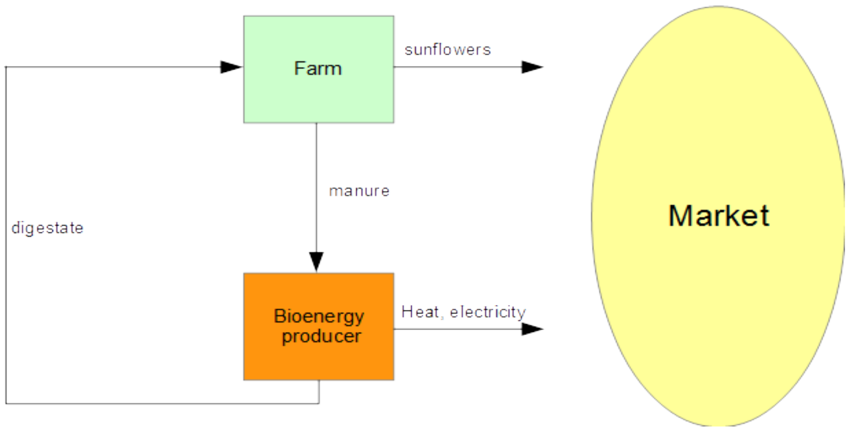

Figure 3. Actors involved in the manure-based biogas supply chain

In traditional production systems, farmers are not involved in energy production because they are mainly concerned with livestock farming. There are other feedstocks that can be used in biogas production instead of manure. Then, what motivates both actors to cooperate?

First, from an economic perspective, intensive livestock farming results in high quantities of manure which exceeds the manure-based fertilizer demand (De Korte, 2012). Second, regulatory constraints on manure use as a substitute of fertilizer allow farmers only to use/sell limited amounts of manure (De Korte, 2012). Both situations influence the economic performance of farmers leading to high manure disposal costs. The bioenergy producer, on the other hand, would have the advantage of producing a by-product to gain higher value-added, i.e., digestate.

From an operational perspective, the ammonia within digestate, differently from nitrogen in raw manure, is immediately absorbed by the soil. In this way, it directly contributes to plant growth. Digestate has three other remarkable advantages for the agricultural practice: (i) it does not present the odor nuisance, providing increased land application options; (ii) it makes weed control easier and more efficient for farmers, destroying unwanted weeds and (iii) plant propagules; it is more homogenous, which makes fertilizer spreading more uniform.

Let us present the equations related to the benefits for both actors from cooperation and then perform computational experiments for five critical variables to understand how the cooperation is influenced.

We now present the benefits from cooperation versus non-cooperation. The subscript ***f*** refers to the farm, ***b*** to the bioenergy producer. The superscripts "**(*0*)**" and "***(1)***" indicate the scenario of no cooperation and cooperation, respectively.

For the farmer the benefit from cooperation is given by:

$$B_f = R_f^{(1)} - R_f^{(0)} \tag{12}$$

where

B_f : Farm benefits from cooperation

$R_f^{(0)}$: Farm revenues in case of no cooperation

$R_f^{(1)}$: Farm revenues in case of cooperation

For the bioenergy producer the benefit is given by:

$$B_b = R_b^{(1)} - R_b^{(0)} \tag{13}$$

where

B_b : Bioenergy producer benefits from cooperation

$R_b^{(0)}$: Bioenergy producer revenues in case of no cooperation

$R_b^{(1)}$: Bioenergy producer revenues in case of cooperation

We assume that the bioenergy producer pays for manure transportation and the farmer pays for digestate transportation. Sunflowers price and production costs remain constant in both scenarios. Production costs of the bioenergy producer are attributed to the operating costs (i.e., biogas production costs, digestate production costs, cost of mixing, and heat production costs).

We introduce C^i, P^i, Q^i to denote the unitary cost of production, the unitary market price, and the quantity produced of the *i*-th element respectively. E and H indicate the electricity and heat produced from bioenergy producer. Finally, $C_f^{discharge}$ is the unitary cost of manure discharge and $P_b^{government\ incentive}$ is the incentive provided by government per unit biomass-based electricity production. Then, we can compute $R_f^{(0)}$ and $R_f^{(1)}$ as follows:

$$R_f^{(0)} = P_f^{sunflowers} * Q^{sunflowers(0)} - C_f^{sunflowers} * Q^{sunflowers(0)} - C_f^{discharge} * (Q^{produced\ manure(0)} - Q^{used\ manure\ (0)}) \tag{14}$$

$$R_f^{(1)} = P_f^{sunflowers} * Q^{sunflowers(1)} + P_f^{manure(1)} * Q^{manure(1)} - P_b^{digestate(1)} * Q^{digestate(1)} + - C^{digestate\ transportation} * Q^{digestate(1)} - C_f^{sunflowers} * Q^{sunflowers(1)} \tag{15}$$

$R_b^{(0)}$ and $R_b^{(1)}$ can be calculated as:

$$R_b^{(0)} = 0$$

$$R_b^{(1)} = E^{produced(1)} * P_b^{electricity} + H^{produced(1)} * P_b^{heat} + E^{produced(1)} * P_b^{government\ incentive} + P_b^{digestate(1)} * Q^{digestate(1)} + - E^{produced(1)} * C_b^{operating(1)} - P_f^{manure(1)} * Q^{manure(1)} - C^{manure\ transportation} * Q^{manure(1)} - C^{amortization\ (1)} + - C^{other\ biomass\ purchase(1)} \tag{16}$$

In order to understand how uncertainty affects cooperation among actors, we identify five variables and investigate their impact on the implementation of the supplier-buyer relationships in the local manure markets. These variables are identified as critical operational, technical, and economic variables. We use three fixed values for each variable as follows:

- Manure quantity (t/year): 5,000 t for a small-scale farm and plant, 20,000 t for a medium-scale farm and plant, 100,000 t for a large-scale farm and plant
- Transportation distance between farm and bioenergy plant (2, 10, 30 km)
- Manure dry content (8 - 10 - 12 %) and organic matter content of manure (80, 82, 85 %)
- Manure price (-5, 0, 5 €/t)
- Manure discharge cost (5, 10, 15 €/t)

These variables have critical importance for operational efficiency and economic performance of the manure-based biogas supply chain. Manure quantity is decisive on plant scale in the cooperation scenario, and on fertilizer use and discharge costs in the non-cooperation scenario. Transportation distance has significant impact as the manure has a very low value which is an obstacle for long distance transportation and consequently influences transportation costs. Manure dry content and organic matter contents are critical for the biogas and digestate yields. Manure discharge cost is also a critical variable, particularly when the bioenergy producer is a unique alternative to manure discharge. Accordingly, we assume that the biogas producer does not pay more than the discharge cost to the farmer in the cooperation-case. Concerning the manure price, -5 €/t indicates that farmer pays bioenergy producer to supply its manure, 0 €/t that manure is sent to the bioenergy producer for free, 5 €/t refers to the case in which bioenergy producer pays farmer to receive its manure.

The amount of other biomass, i.e., corn silage, mixed with manure (2% of the blend), the available cultivation land (1000 hectares), and manure application rate (10 t/ha) are assumed constant.

Considering that biogas production from cattle manure was not profitable in our base scenario analysis (see Table 2) and swine manure has a higher biogas yield, we use swine manure data for our computational experiments.

5. Results and discussion

We apply computational experiments based on what-if scenarios. Considering three values for each variable, in total we obtain 243 different combinations. These combinations represent the effects of uncertainty characterizing cooperation dynamics. In this section, we show the most relevant results, some of which display combined effects of the variables.

Impact of manure quantity

According to Figure 4, manure quantity notably affects cooperation benefits. For a small & medium-size farm (<= 20,000 t of manure/year) the benefits are negative. For the bioenergy producer, the higher the scale, the higher the benefits from cooperation.

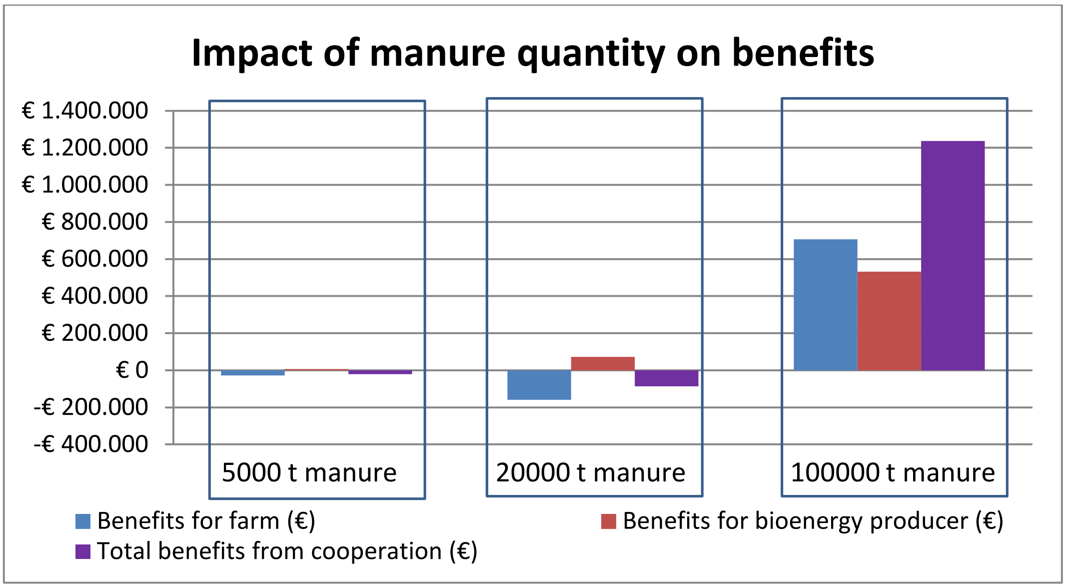

Figure 4. Impact of manure quantity on benefits (with a fixed manure price (0 €/t), manure dry content (12%), organic matter content (85%), transportation distance (2 km), manure discharge cost (15 €/t))

Impact of manure price and manure quantity

Figure 5 shows the impact of manure price and quantity on actors' benefits. When the farmer pays the bioenergy producer to supply its manure (manure price = - 5 €/t), farm benefits are negative in case of small-medium scale. In such a case, the benefits for the large-scale bioenergy producer is the highest.

When the bioenergy producer pays the farmer for the manure (manure price = 5 €/t), the benefits for the bioenergy producer are negative in case of small-medium size plant. The large-scale farmer benefits the most.

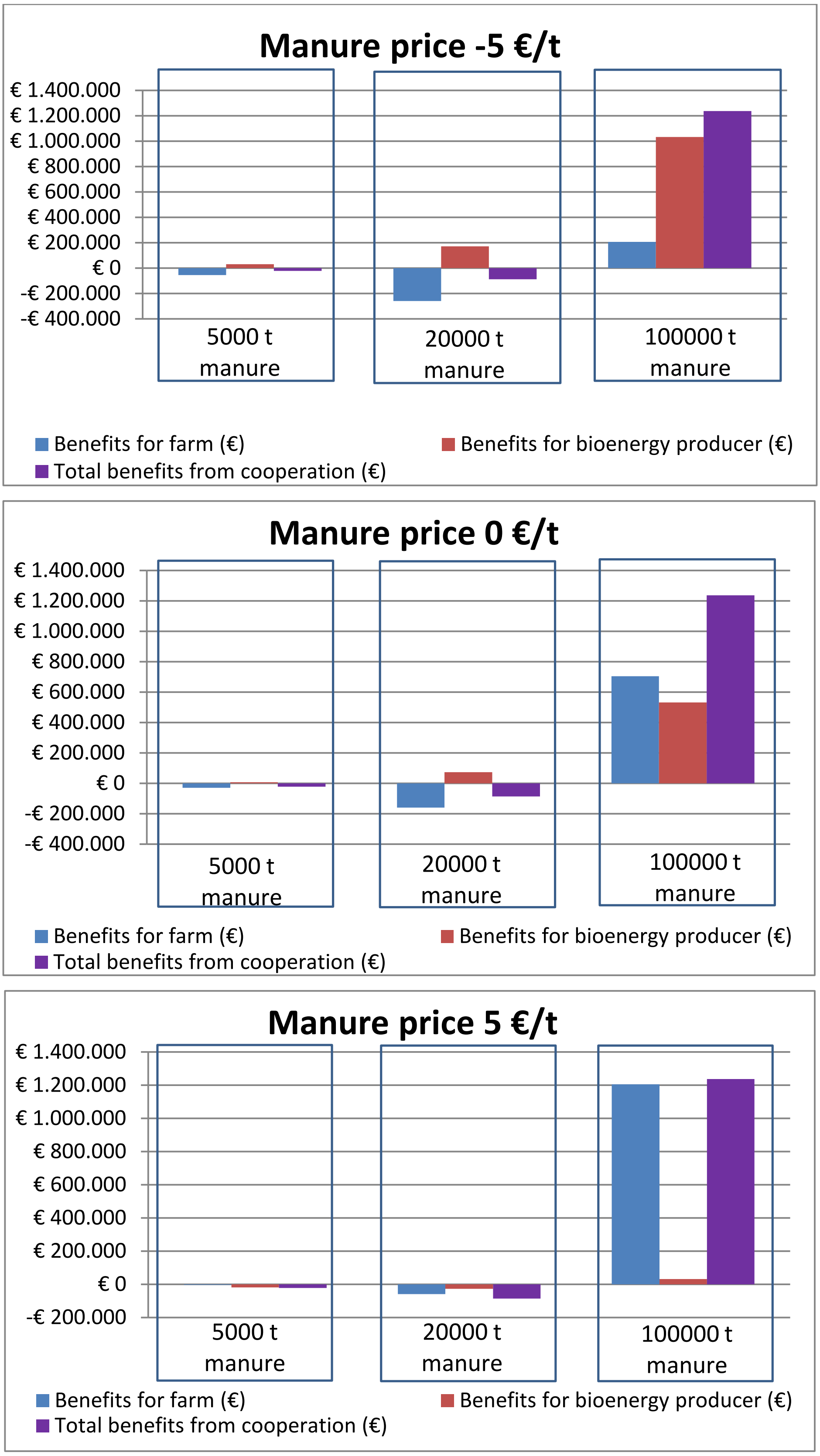

Figure 5. Impact of manure price and manure quantity on benefits (with a fixed manure dry content (12%), organic matter content (85%), transportation distance (2 km), manure discharge cost (15 €/t))

Impact of manure dry content and manure quantity

Figure 6 displays the impact of manure dry content (and organic content) on cooperation dynamics. Expectedly, if manure dry content is high, cooperation benefits increase.

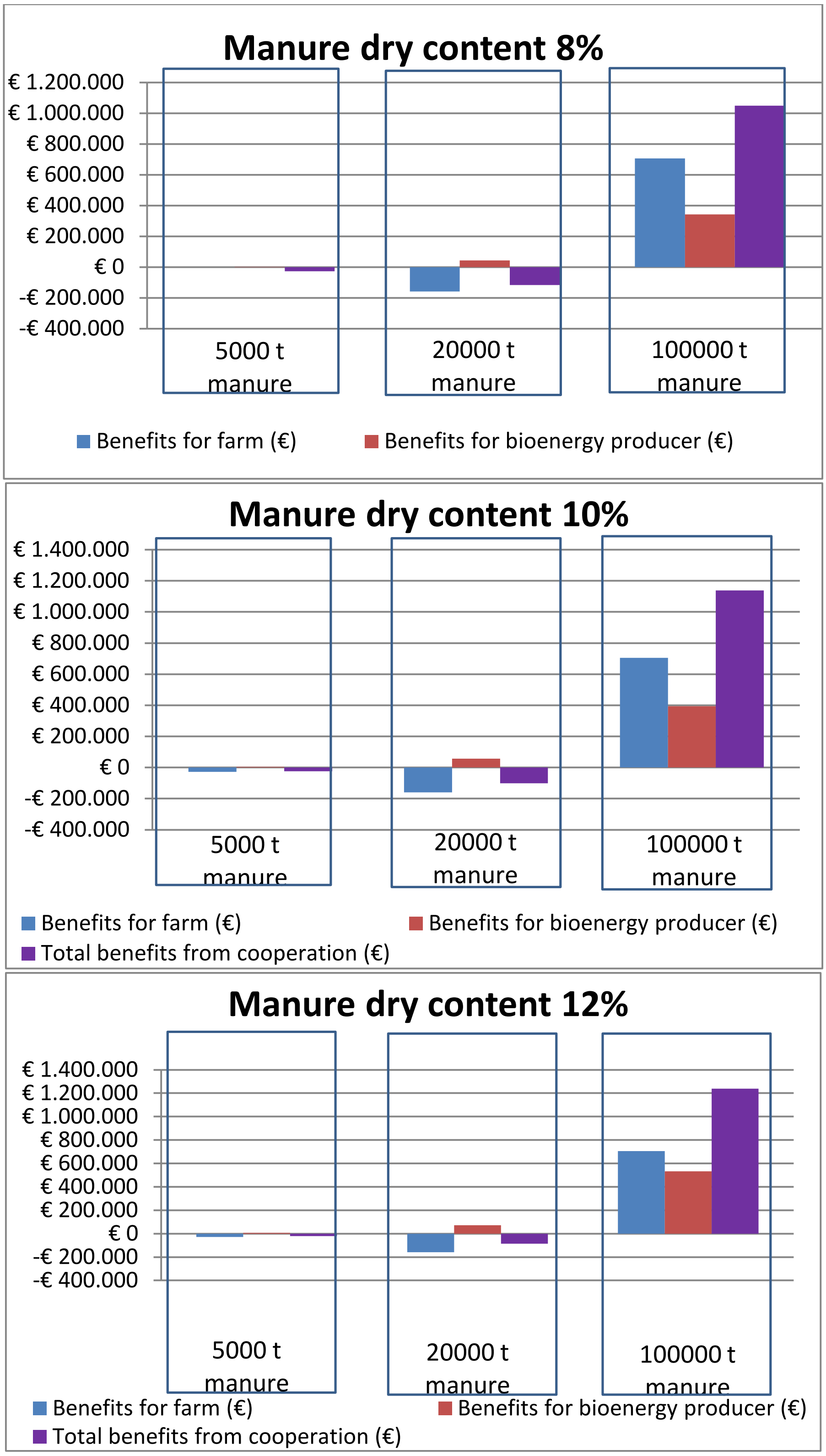

Figure 6. Impact of manure dry content and manure quantity on benefits (with a fixed manure price (0 €/t), transportation distance (2 km), manure discharge cost (15 €/t))

Impact of transportation distance and manure quantity

According to Figure 7, the shorter the transportation distance, the greater the benefits arising from cooperation. The impact increases with increasing farm- and plant-scale.

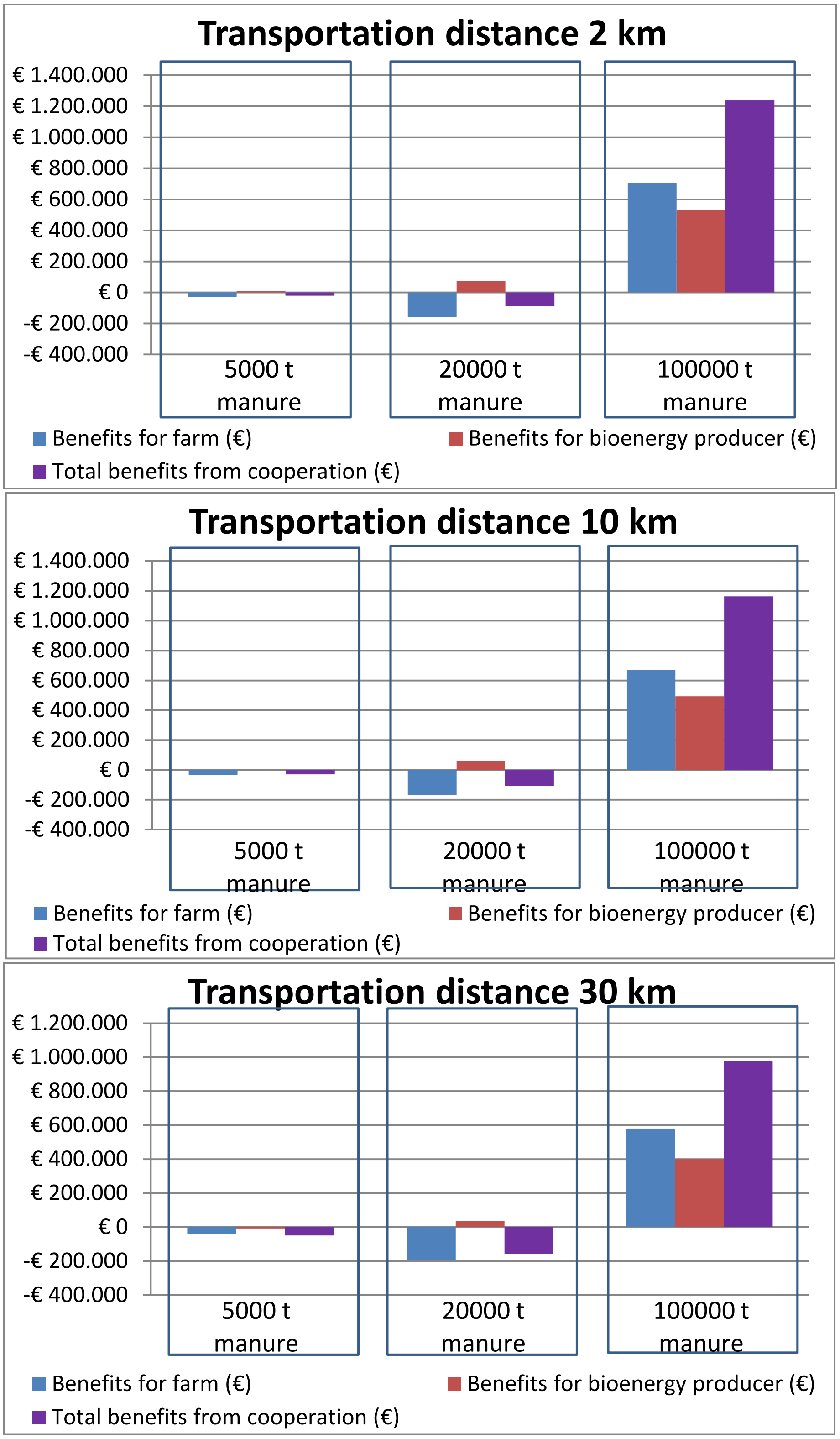

Figure 7. Impact of transportation distance and manure quantity on benefits (with a fixed manure price (0 €/t), manure dry content (12%), organic matter content (85%), manure discharge cost (15 €/t))

Impact of manure discharge cost and manure quantity

Farm benefits depend on manure discharge cost (Figure 8). If discharge costs are high, the farm revenues in case of non-cooperation decrease because the remaining amount of manure, not usable as fertilizer, has to be disposed of. On the other hand, the bioenergy producer is not affected by the discharge cost.

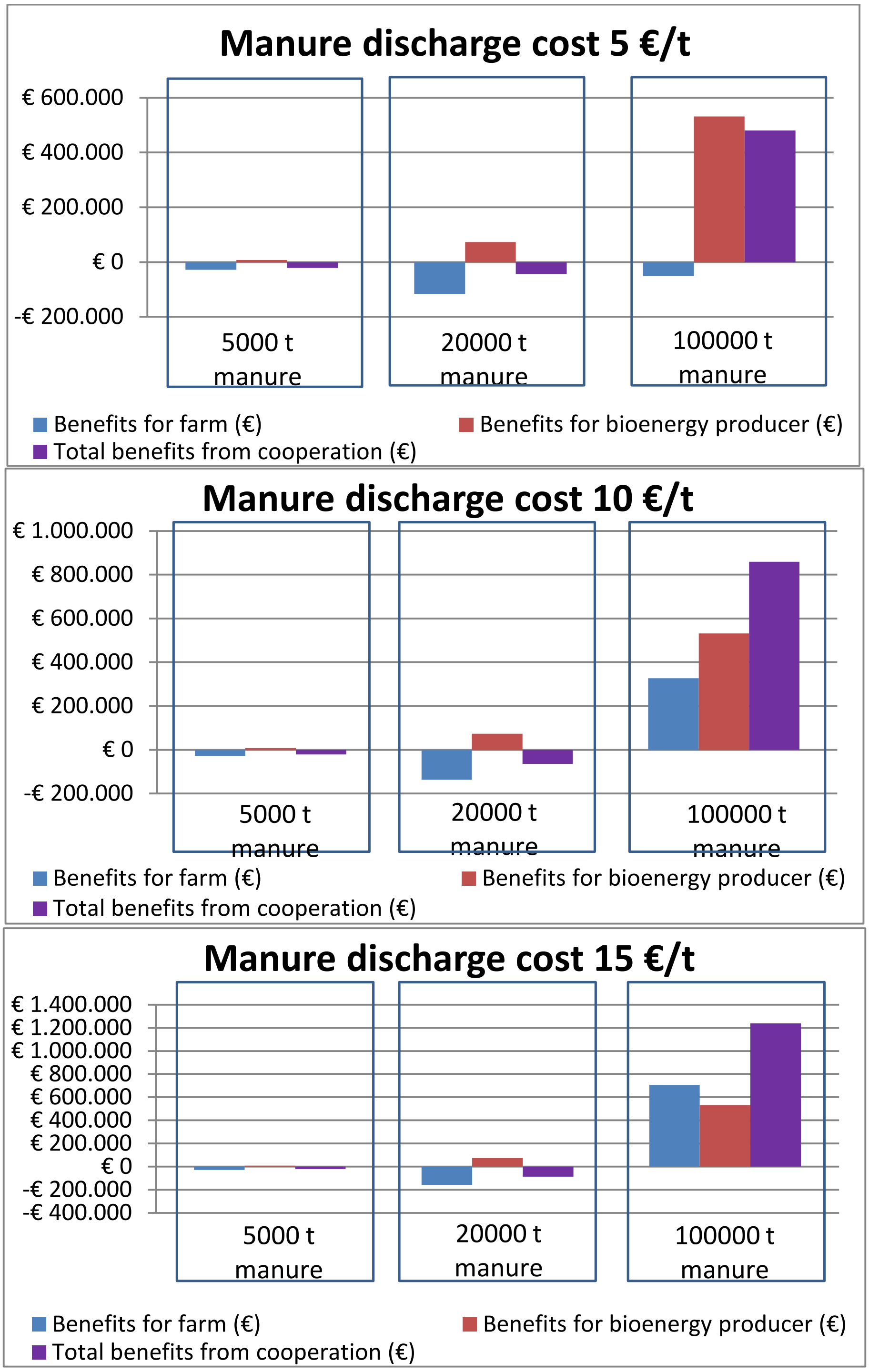

Figure 8. Impact of manure discharge cost and manure quantity on benefits (with a fixed manure price (0 €/t), manure dry content (12%), organic matter content (85%), transportation distance (2 km))

However, depending on the case, manure discharge costs might provide an idea to the bioenergy producer about the manure price to offer to the farmer. Our next analysis is based on the combined effect of manure discharge cost and manure price.

Impact of manure discharge cost and manure price on benefits

In Figure 9, we present the combined effect of manure discharge cost and price on cooperation dynamics for a big-scale plant, having revealed in precedent analyses that big-scale cooperation is more advantageous.

The farm has the highest benefit when manure discharge cost is 15 €/t and manure price is 5 €/t (bioenergy producer pays farmer to receive its manure). Bioenergy producer's benefit reaches a peak if manure price is -5 €/t (when he is paid by farmer to receive its manure), regardless of the discharge cost (Figure 9).

Summarizing (Figures 4-9), cooperation is not profitable for a small-medium-scale farm (<= 20,000 t/year). It is profitable for a large-scale farm if ***b*** pays ***f*** to receive its manure (5 €/t), regardless of the values of other variables; or if ***f*** provides its manure for free and manure discharge costs are high (10-15 €/t); or if ***f*** pays ***b*** to supply its manure (5€/t) and at the same time manure disposal costs are very high (15 €/t).

Cooperation is always profitable for a bioenergy producer if ***f*** pays ***b*** to supply its manure (5€/t). If ***b*** receives manure for free, benefits from cooperation are always positive if ***b*** is a medium-large-scale plant (> 10,000 t/year). On the other hand, (if manure is free) for a small-scale ***b***, benefits are positive only if manure dry content is high (MDC=12%) and transportation distance is small (<= 10 km). If ***b*** pays ***f*** to receive its manure (5 €/t), ***b*** benefits are always negative except when manure quantity processed is >= 100,000 t/year (large-scale bioenergy plant), MDC=12% and transportation distance is very small (<= 2 km). We notice that manure quantity and manure price have the strongest impact on cooperation dynamics, because they significantly affect the benefits for both actors.

These results allow us to better understand the potential of cooperation through supply chain actors in the context of developing a local circular economy business model. Indeed, our results show that such a mechanism provides an effective use of existing local resources, particularly when the quantity of supply is high and the bioenergy plant uses the advantage of economies of scale. Small- and medium-size plants can also be advantageous under certain conditions discussed above.

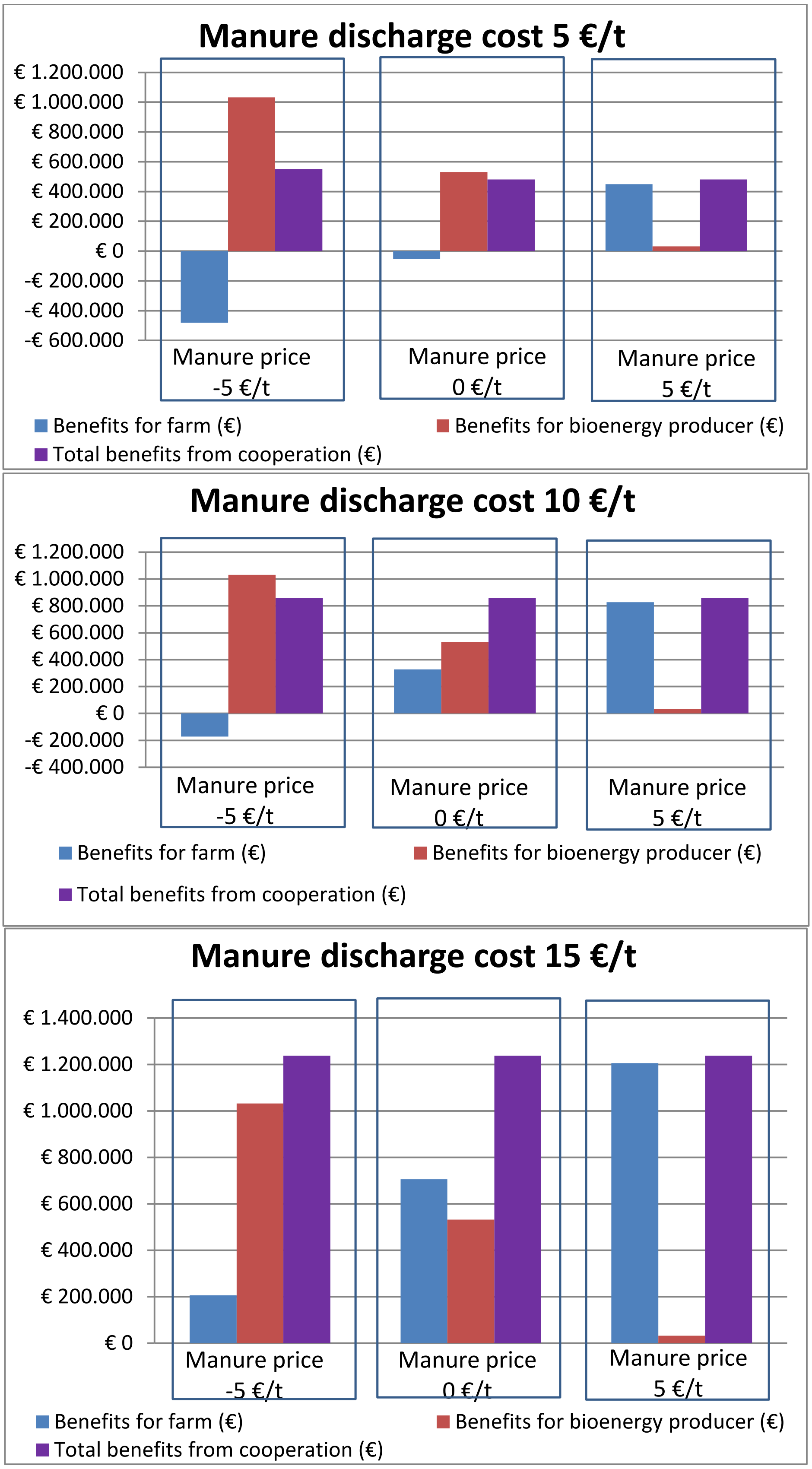

Figure 9. Impact of manure discharge cost and manure price on benefits (with a fixed manure quantity (100,000 t), manure dry content (12%), organic matter content (85%), transportation distance (2 km))

Based on the results of our analysis, in some cases, cooperation can be beneficial for one actor while the other one has negative economic return. However, when the total benefit is still positive, then, in order to foster cooperation, benefits could be shared between the two actors. How companies can implement benefit-sharing schemes should be further investigated in future research.

Furthermore, the cooperation scenario has other remarkable advantages from technical, environmental, and social perspectives. In comparison to untreated manure, anaerobic digestion of manure brings along multiple additional benefits, like decreasing methane emissions and odor nuisance, as well as increasing the hygienic status and nutrient availability of manure.

6. Conclusions

While the production of bioenergy from manure via anaerobic digestion has been largely studied in the literature, few studies have investigated the cooperation dynamics among actors within the manure-based biogas supply chain. Our paper fills this gap, in order to understand under which conditions cooperation can be beneficial or detrimental to actors involved in the supply chain.

The benefits of the cooperation are strongly influenced by several technical, operational, and economic variables whose impacts are quantified via scenario analysis. Such variables represent the effect of uncertainty on the supplier-buyer relationships in local manure markets, where waste technical quality, price, and quantity vary over time. In particular, we apply computational experiments to reveal the role of such variables aimed at enhancing the development of a circular economy business models on a local level.

Considering that animal farming and cultivation activities are mostly performed in rural areas, our business model provides a closed-loop supply chain to reduce environmental impacts of secondary outputs of such activities in rural areas. The business model can be extended to a case where manure is used for biogas production, digestate is used for fertilization, agricultural residues are used as a blending biomass, and the bioenergy produced is used instead of fossil-based energy in animal-farming and cultivation activities. This would be a complete circular model in line with the EU’s regional development strategies, particularly when we consider that the sustainable development should be on local level. Implementing sustainability at on a local level involves efficient cooperation of local business actors on efficient use of local resources and the suitable conditions are promoted by regional authorities. Hence, our case can also be considered as a regional development model.

Several assumptions of our paper should be dealt with in future research. Our business model considers a simple case of a one-on-one relationship in which only two actors are involved in the biogas supply chain. However, we should consider that there might be multiple farmers or biogas plants according to the available manure quantity in a region. For example, if there are ten farms producing different amounts of manure under same conditions, then the benefit will be proportionally divided among them, meaning that each farmer gains much less than the bioenergy producer. This also means different levels of bargaining power and willingness-to-cooperate for each supplier and biogas plant might appear and total economic benefits calculated in Section 4 might be distributed among involved actors according to potential contracts or benefit-sharing schemes. Similarly, other actors, such as intermediaries between suppliers and buyers or third-party logistics players or farmer coalitions might be involved in such a business model and the network, then, must be modelled with these multiple actors. In fact, further research should assess the managerial conditions of such supplier-buyer networks where small, medium, and big-scale farms and plants are located randomly. Hence, simulation techniques such as agent-based modelling can be used to evaluate different cooperation strategies of these multiple actors.

Furthermore, we assume that in the cooperation scenario, all of the produced manure is sold to the bioenergy producer, i.e., the demand is equal to supply. So, our model can be used by biogas producers as decision support to invest in biogas production considering a one-on-one relationship. However, supply-demand match is critical and if there is surplus or lack of manure, then the economic benefits might fluctuate, which can also be dealt with simulation techniques. Such a technique is also useful to address the dynamicity of the circular business model which evolve over time. Further research will aim at extending our study to a more complex scenario in which more suppliers and buyers are involved in a network.

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